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Compensation of the Temperature Coefficient in a Hybrid Permanent Magnet.

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Abstract

During a workshop about PM Storage rings in November 1004, it was suggested by K. Bertsche to correct the undesirable consequences of the temperature coefficient of the remanent field of the Charge Sheet Equivalent Material (CSEM) to be used in hybrid magnets by using the temperature coefficient of a ferromagnetic flux shunt. It is the purpose to derive in this note a figure of merit that allows one to decide whether such an approach is useful, and what material should be used.[1]

[1] This document was supplied with the title shown on the next page. To comply with the 80 character limit of MTF Document Titles, I have shorted it to the title above. This was provided to the Recycler working group in May 1995. Bruce Brown

Compensation of Some Consequences of the Temperature Coefficient of the Remanent Field of Permanent Magnet Material in a Hybrid Magnet.

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1) Introduction

During a workshop about PM storage rings in November 1994 it was suggested by K. Bertsche to correct the undesirable consequences of the temperature coefficient of the remanent field of the Charge Sheet Equivalent Material (CSEM) to be used in hybrid magnets by using the temperature coefficient of a ferromagnetic flux shunt. It is the purpose to derive in this note a figure of merit that allows to decide whether such an approach is useful, and what material should be used.

2) Definition of Model and Symbols.

I assume that the flux shunt consists of one or more sheets of ferromagnetic material that connect the iron pole of the magnet to the iron yoke (often called the box) in a region of essentially uniform H-field, with the thin dimension of the sheet being perpendicular to the direction of the H-field. I assume further that H is large enough that the material is so strongly magnetized that the B(H) curve in this field region can be described by

(2.1) $B=H+M_S$.

Indicating a derivative with respect to temperature T by ', the thermal properties of the magnetization M_S is given to lowest order by the temperature coefficient

(2.2) $D_S=M_S'/M_S$.

For the CSEM I assume similar relationships

(2.3) $B=H+B_r$

(2.4) $D_r=B_r'/B_r$.

If it is necessary to take the differential permeability of the CSEM into account, I multiply H in equs.(2.1) and (2.3) by that permeability, making a very small, but obviously never noticeable, error in equ.(2.1) since that permeability is very close to one.

3) The Magnetostatic Equations Governing the Field B_0 in the Gap

I represent the CSEM by magnetic charge sheets and assume (for the typical box magnet of any multipolarity) that they touch either surfaces of the block of iron that constitutes the pole, or the surrounding iron box. The flux shunt is assumed to connect these blocks of iron in the same way, subject to the condition stated in section 2. Assuming all iron, except the shunt, having infinite permeability, the field B_0 at some point of interest in the gap can be extracted from

(3.1) $B_0 A_0 = B_r(A_t - A_S) - M_S A_S$.

The left side of this flux balance equation represents the total flux leaving the pole-block, being on a scalar potential (relative to the box) that is proportional to the desired B_0, taking into account the differential permeability of the materials, but ignoring B_r and M_S. With A_t representing the total area of both CSEM and shunt material that touches pole surfaces, and A_S representing the surface of the shunt material touching the pole, the right hand side of equ.(3.1) describes the flux contribution to the pole generated by the active material, and "lost" by the shunt.

4) Design for First Order Temperature Independence, and Associated Figure of Merit

The condition for first order temperature independence of B_0 clearly is

(4.1) $B_r'(A_t - A_S) = M_S' A_S$,

yielding

(4.2) $A_S/A_t = 1/(1+M_S'/B_r') = 1/(1+M_S/B_r * D_S/D_r)$

as a design equation. Using this in equ.(3.1), that equation can be rewritten as

(4.3) $B_0 A_0 = B_{reff} A_t$,

with

(4.4) $B_{reff} = B_r F$.

F is the figure of merit and is given by

(4.5) $F = (1 - D_r/D_S)/(1 + B_r/M_S * D_r/D_S)$.

5) Use of, and Comments to, Equs.(4.3)-(4.5).

The great advantage of these equations is that in order to design a hybrid magnet with a shunt one can use the "normal" procedure to design hybrid magnets, but by using B_{reff} instead of B_r one accounts for a shunt that is designed to give temperature insensitivity to first order. This means also that "cost" associated with this shunt compensation is immediately qualitatively and quantitatively apparent. Specifically, knowing that in a large region of parameter space the amount of active CSEM material is inversely proportional to the square of the remanent field, it becomes clear that the amount of CSEM would go up roughly by a factor $1/F^2$. The figure of merit also makes it easy to decide which of the materials that have large M_S, large D_S (and saturate at modest H) is the best material when paired with a particular CSEM. It is also noteworthy that the "best" choice for shunt material is dependent on the field in the gap only indirectly, namely through the choice of the CSEM.

6) Generalizations

Even though it has been assumed for the sake of simplicity that all surfaces of CSEM with magnetic charges touch iron, dropping that condition (as is necessary when one incorporates fine field level tuning with the help of rotatable CSEM blocks) does not substantially modify the equations, except that A_r assumes a slightly different meaning. While it is probably preferable to have the shunt material ends touch iron, even that is not absolutely necessary. But the whole description of the effect of the shunt material does assume that the unperturbed field is parallel to a long dimension of the shunt material. In the unlikely event that one has to correct temperature changes to second order, this can be accomplished by using two shunts with different magnetic characteristics.